

Studies of Hadron Structure and Interactions with the $\overline{\text{PANDA}}$ Experiment at FAIR

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The $\overline{\text{PANDA}}$ experiment together with the high quality antiproton beam at HESR will be a powerful tool to address fundamental questions of hadron physics in the charm and multi-strange hadron sector. In connection with the recent data in the hidden charm sector, $\overline{\text{PANDA}}$ will be able to deliver decisive contributions to this field, due to the complementarity of the $\overline{p}p$ entrance channel and the capabilities of the combined storage ring and detector system under construction.

I. INTRODUCTION

The modern theory of strong interactions, Quantum Chromodynamics (QCD), displays a very rich array of non-perturbative phenomena, many of which are not yet understood. Progress in this respect will impact a broad range of physical problems, in settings ranging from astrophysics, cosmology to strongly coupled complex systems in particle and condensed matter physics [1]. Furthermore, hadronic effects often represent the dominant uncertainties in the tests of various fundamental quantities in the Standard Model (e.g. the muon $(g - 2)$).

$\overline{\text{PANDA}}$ will measure annihilation reactions of antiprotons with nucleons and nuclei in order to provide complementary and in part uniquely decisive information on a wide range of QCD aspects. The $\overline{p}p$ entrance channel not only couples very strongly to the gluonic components of produced hadrons and of allowing resonant production of e.g. quarkonium states, but also allows a wide range of quantum numbers of the produced system. Quarkonia, i.e. bound systems of two heavy quarks, have been instrumental in the establishment of QCD, and have again a central role, thanks to challenging and exciting data from BaBar, Belle, BESIII and the LHC.

The scientific scope of $\overline{\text{PANDA}}$ is ordered into several pillars: hadron spectroscopy, properties of hadrons in matter, nucleon structure and hypernuclei. Each of these pillars addresses specific open issues of QCD.

Hadron spectroscopy is currently characterized by the fact that many predicted states have not yet been found while others were observed, which do not fit to expectations. Candidates for hybrid, molecular, and tetraquark systems have been discovered. Charged, and thus manifestly exotic states have been detected. All these results indicate that some crucial pieces of the puzzle are missing. Success in achieving a theory description of quarkonium processes and of the new states impacts our understanding of QCD and strongly coupled systems at a deeper level and also helps us to address other fundamental questions in particle physics and nearby fields [2].

$\overline{\text{PANDA}}$ will be able to carry out a comprehensive study of charmonium physics, both in direct formation and in production modes (see below), providing unique information, which will be complementary to e^+e^- ex-

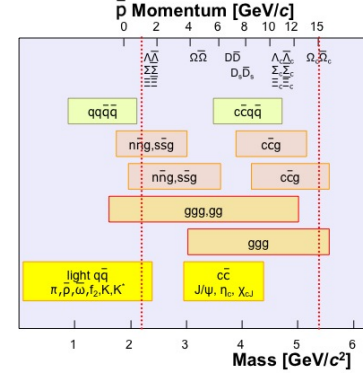


FIG. 1. Overview of the spectroscopic states accessible in $\overline{p}p$ annihilation as a function of antiproton momentum (upper scale) or cm energy (lower scale). The red dashed lines indicate the range accessible with $\overline{\text{PANDA}}$ at HESR.

periments (Belle2, BESIII, limited to low spin states (mainly vector and axial)) and to the LHC, which will study quarkonium production for much higher energies. A schematic overview of the relevant states is in Fig. 1. As indicated, there will not only be studies of charmonium(-like) states, but also searches for and investigations of states with strong gluonic contributions to the wavefunction, i.e. glueballs and hybrids, are foreseen.

$\overline{\text{PANDA}}$ will address two important issues connected to hadrons in a nuclear environment. First, in-medium modifications of hadronic properties will give precious information on the mechanism of chiral symmetry breaking and its partial restoration. Second, the measurement of charm production cross sections in \overline{p} annihilation on a series of nuclear targets, will allow to deduce the hidden/open-charm nucleus dissociation cross sections. These are fundamental to understand charmonium suppression in relativistic heavy ion collisions, which is interpreted as a signal for quark-gluon plasma.

In the study of nucleon structure, recent progress in theory has concerned the formulation of methods to define and calculate with nonperturbative approaches parton physics and generalized distribution functions. Experimental extractions of these quantities are plagued by many uncertainties that limit our knowledge of other

quantities. $\bar{\text{PANDA}}$ will be able to contribute in this field by measuring the crossed-channel counterparts of the processes that are studied by lepton scattering experiments in many laboratories e.g. DESY, CERN, JLAB.

For the baryonic sector, $\bar{\text{PANDA}}$ can access many systems for detailed studies of spectroscopy and production cross section. Furthermore, the study of hyperon's production will give access to hyperon-nucleus and hyperon-hyperon interaction mechanisms which have implications in particle and nuclear physics.

To illustrate where $\bar{\text{PANDA}}$ will make major contributions in this context, we focus in the following on just three specific topics for which we discuss not only the physics, but also in which respects $\bar{\text{PANDA}}$ will be superior and/or complementary to other experiments. These topics are open charm states, in particular the $D_{s0}(2317)$, quarkonium and quarkonium-like states, in particular the $X(3872)$, and the field of hypernuclei and hyperons. This small selection from the many aspects of the $\bar{\text{PANDA}}$ physics program is made to stress both the importance of charm physics and the possibility to explore novel aspects of cold nuclear matter.

II. OPPORTUNITIES WITH ANTIPROTON ANNIHILATION

Antiproton-proton annihilation often proceeds via two or three-gluon processes. Consequently, as shown at LEAR, this system is very favorable to study gluonic degrees of freedom compared to other processes where valence quarks and antiquarks can suppress the production of glueballs. It was demonstrated by the LEAR experiments at CERN [3, 4] and the E760/E835 experiments at Fermilab [5, 6] that the combination of an intense, nearly mono-energetic antiproton beam with a state-of-the-art 4π experiment is ideally suited for the field of spectroscopy. In these experiments not only the most prominent glueball candidate, the $f_0(1500)$, was discovered, but also the relevant PDG results are dominated by their precision. This is due to the unique features offered by cooled antiproton beams combined with dedicated detectors. $\bar{\text{PANDA}}$ will be the first experiment capable to measure both charged and neutral particles with a truly 4π -detector exploring the energy regime of charm with this high precision.

The use of antiproton-proton annihilation enables two modes to investigate resonances at $\bar{\text{PANDA}}$. In the *formation* mode a single resonance is formed directly in the annihilation process, which correspondingly must have J^{PC} quantum numbers accessible by a fermion-antifermion pair. In contrast, the *production* mode involves at least one additional particle to the resonance of interest, which thus does not have the same restrictions on J^{PC} . The comparison of both methods helps to classify the resonances and identify those with exotic quantum numbers, i.e. quantum numbers forbidden for ordinary quark-antiquark mesons. In general, no restric-

tions for quantum numbers of resonances produced in $\bar{\text{PANDA}}$ exist, all states can be populated. Since charmonia often decay to final states containing lepton pairs, which are otherwise rare at these energies in the hadronic environment, $\bar{\text{PANDA}}$ can often profit from clean signal/background ratios.

For those newly discovered X, Y, Z states that possess a very narrow width, a precise determination of the excitation curve is necessary to distinguish between the different theoretical interpretations. This can be done decisively better with $\bar{\text{PANDA}}$ in formation mode due to the strong phase space cooling of the antiproton beam in HESR, compared to the production of these states in the decay chain of heavier particles.

Again, the LEAR experiments demonstrated that the antiproton annihilation is a nearly ideal way to produce baryon-antibaryon pairs with strangeness. This is especially the case close to the corresponding production thresholds, where very clean experimental conditions occur due to the large cross sections and the effective detection of forward-going particles in the forward detector. In contrast to other experiments, $\bar{\text{PANDA}}$ has a special design consisting of a dipole magnet in the forward spectrometer that bends the accelerator beam away from the zero-degree region. Thus, basically the full solid angle for decay products is covered, providing an enormous advantage for the threshold experiments and for the determination of the quantum numbers of states with the help of amplitude analysis. For the production of hypernuclei or for the implantation of strange or charmed baryons in nuclear matter, the existence of a pair of particle and antiparticle provides the unique advantage that the detection of either one of them provides an excellent trigger to select reactions of the partner inside nuclear matter.

III. SELECTED EXAMPLES

Threshold Scan of the $D_{s0}^*(2317)$

An excited hadron state for which so far there exists great uncertainty is the $D_{s0}^*(2317)$. Can it be described more adequately as a two meson molecule with a leading four quark Fock state or as a conventional meson with a leading two quark Fock state? The problem lies in the fact that in QCD one always faces a configuration mixture of all field configurations with the same quantum numbers. Consequently, this is rather a quantitative than a qualitative question which should be formulated as: With which amplitude do the leading Fock state components enter the $D_{s0}^*(2317)^\pm$ wave function within a specific factorization/renormalization scheme at a specific scale? From the theory side, first steps to answer such questions rigorously were taken using lattice QCD [7, 8]. While these calculations are still only exploratory they demonstrate clearly that by the time $\bar{\text{PANDA}}$ will start to take data, precise predictions from the lattice should be available. Technically, this requires full-fledged variational calculations with physical quark masses, which

will become possible based on the foreseeable increase in computer power within just a few years.

Experimentally one can test these calculations by measuring precisely the partial widths for the various decay channels of the $D_{s0}^*(2317)^\pm$ and the other D_s mesons. While hadron masses are usually not very specific for the physical nature of the state under discussion, the individual decay widths are. For example, the $D_{s1}^*(2536)$ decays into DK channels and is thus especially sensitive to any DK component in its wave function, for instance theoretical predictions for $D_{s0}^*(2317)^\pm \rightarrow D_s + \pi$ range from $\Gamma = (6 \pm 2)$ to 140 keV.

Once the nature of the $D_{s0}^*(2317)^\pm$ is unambiguously clarified by such a combined experimental and lattice approach, one can then use the results to formulate a controlled low energy description in terms of hadronic degrees of freedom. This description would allow to address also those experimental results which are not accessible to LQCD, for example real time reaction properties of the D_s states, as illustrated in, e.g. [9].

The PANDA experiment will be able to make decisive contributions to understanding the nature of the $D_{s0}^*(2317)$ by performing a high precision measurement of the total width. This is achieved by analyzing the excitation function of the reaction $\bar{p}p \rightarrow D_{s0}^*(2317)^\pm D_s^\mp$ within ± 2 MeV of the nominal threshold [10]. Since theoretical calculations of the cross section for this process vary significantly, it is not possible to quote the exact precision for the width determination. For a 1 nb production cross section at 5 MeV over the nominal threshold, the precision to measure the total width varies from 25 to 50 keV, depending upon the actual value of the width. This precision is about two orders of magnitude more sensitive than the current upper limit of 3.8 MeV, which is not expected to be significantly improved below the MeV range by other experiments in the foreseeable future. Thus PANDA will confirm or exclude a large fraction of the predicted range $\Gamma \sim 6 - 140$ keV expected from theoretical calculations, thereby making a decisive contribution to the understanding of the nature of this potentially exotic state.

Resonance Scan of the $X(3872)$

The $X(3872)$ was first observed by Belle [11] and was subsequently confirmed at BaBar, CDF, D0, LHCb and BESIII. Its main features are a very small width ($\Gamma < 1.2$ MeV), a mass which is close to the $D^0 D^{*0}$ threshold and quantum numbers $J^{PC} = 1^{++}$. As the first new state to be discovered the $X(3872)$ is also the best studied but, despite this, its nature remains unknown. Possible interpretations include conventional charmonium, diquark anti-diquark bound state, a tetraquark state or a molecular state, and the line shape of this state is expected to be a sensitive method to discriminate between the binding mechanisms [12].

Theoretical estimates of the cross section for $X(3872)$ formation in $\bar{p}p$ annihilations with a subsequent decay to $J/\psi \pi^+ \pi^-$ have been done in a model-dependent way in [13] and range from 2 to 443 nb, with a strong de-

pendence on the total width of this state, for which the authors have assumed the interval between 136 keV and 2.3 MeV. Experimentally only upper limits are available for the total width (< 1.2 MeV) and the branching ratio to $\bar{p}p$ ($< 2 \times 10^{-3}$) and a lower limit for the branching ratio to $J/\psi \pi^+ \pi^-$ (> 0.026) [14].

A precise determination of the width of this very narrow state is difficult in a production experiment (e^+e^- or pp), because in this environment the state has to be reconstructed and the achievable precision strongly depends on the experimental detector resolution. On the other hand, a high precision measurement is possible in PANDA by means of a resonance scan in the direct formation process $\bar{p}p \rightarrow X(3872) \rightarrow J/\psi \pi^+ \pi^-$. The availability of \bar{p} beams with a beam momentum spread $\Delta p/p = 4 \times 10^{-5}$ (high-resolution mode) makes it possible to measure widths of 100 keV or smaller and makes PANDA a unique experiment to measure these very narrow states. This has been proven by means of detailed Monte Carlo studies [15], in which a 20 point energy scan around the $X(3872)$ was simulated. In order to test the sensitivity of PANDA the simulation was carried out under rather challenging assumptions for the (unknown) resonance parameters: a total width of 100 keV with a cross section of 50 nb for the process $\bar{p}p \rightarrow X(3872) \rightarrow J/\psi \pi^+ \pi^-$, a rather pessimistic scenario, since the theoretical predictions combine small widths with larger cross sections (or vice versa). This combination of parameters corresponds to $BR(X(3872) \rightarrow \bar{p}p) \times BR(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = 3.9 \times 10^{-6}$, perfectly consistent with the current experimental limits. The hadronic background was studied using a Dual Parton Model (DPM) based generator [16]. The results show that the $X(3872)$ can be reconstructed with a signal-to-background ratio of 7 and its width measured as (87 ± 17) keV, consistent with the input width of 100 keV.

These studies demonstrate that PANDA is unparalleled in its ability to perform resonance scan investigations of such narrow states, which can be formed directly in $\bar{p}p$ annihilations.

Production and Spectroscopy of Baryon-Antibaryon Pairs

Surprisingly little has been measured of the excited (multi)strange and charm baryon spectra. This together with the large cross section into baryon-antibaryon final states (e.g. $\sim 1 \mu\text{b}$ for $\Xi\bar{\Xi}$ or $0.1 \mu\text{b}$ for $\Omega\bar{\Omega}$) make spectroscopic studies of excited hyperons a very compelling part of the initial program of PANDA when the luminosity has not yet reached the design value.

In addition to the hyperon spectra, also the hyperon-hyperon interactions are of significant relevance. For example they are an important input for the physics of compact stars [17]. Traditionally, the core of neutron stars has been modeled as a uniform fluid of neutron-rich nuclear matter in equilibrium with respect to the weak interaction. Nevertheless, due to the large value of the density, other hadronic degrees of freedom (*i.e.* hyperons) are expected to appear in addition to nucleons

[18]. Unfortunately, in contrast to the nucleon-nucleon interaction, the fundamental two- (and multi-) baryon forces are poorly known. So far, the world database on Nucleon-Hyperon interaction comprises only a few tens of low-momentum Λ -N and Σ^\pm -N scattering events, very little data on Ξ -N and no data on Ω -N scattering [19]. First lattice [20] and EFT [21] calculations are emerging, but require better experimental information.

Another example to illustrate the relevance of hyperon-hyperon interactions is the search for the H-dibaryon. The H-dibaryon is an exotic system with strangeness $S = -2$, predicted by Jaffe [22] and never observed. The discovery of the ${}^6_{\Lambda\Lambda}\text{He}$ hypernucleus and the measurement of its binding energy [23] has completely ruled out the possibility that this particle could have a binding energy greater than 7 MeV. The only open possibility nowadays is a shallow potential or a molecular system. This state and other strange di-baryons are now amenable to ab initio lattice and also precise EFT studies, see e.g. [24–26]. At PANDA three different double strange systems will be produced: i) exotic hyperatoms (created during the capture process of the Ξ^-); ii) doubly strange hypernuclei (Ξ^- hypernuclei); and iii) $\Lambda\Lambda$ hypernuclei (following the Ξ^- -N interaction). We expect to perform γ -spectroscopy of several tens of double Λ hypernuclei per month when PANDA is running. This has to be compared with less than ten double hypernuclei identified up to now.

Another interesting feature of hyperon study is that they give access to spin observables. The spin of the hyperon can be related to the spin of the individual quarks. As an example, the spin of the Λ hyperon is primarily carried by its valence s quark. Consequently, studying spin variables in the $\bar{p}p \rightarrow \bar{Y}Y$ processes probes the role

of spin in the creation of strangeness. The same argument holds for the creation of charm in the case of the charmed-hyperons.

The non-existence of CP violation in strong interactions is an open question. The amount of CP violation within the Standard Model is far too low to account for the matter-antimatter asymmetry in the universe. It is therefore important to search for other sources. CP violation in the hyperon systems can be one of these. Although the Standard Model CP violation predictions for hyperons give very low values, hyperon CP violation parameters can be sensitive to effects from physics beyond the Standard Model such as supersymmetry, left-right symmetric models and multicharged Higgs [27, 28].

IV. SUMMARY

The PANDA experiment will use intense, phase space cooled beams of antiprotons to enable precision studies of fundamental questions of hadron and nuclear physics in the charm and strangeness sector. Already with the start version of FAIR an impressive program of exploration and precision measurements will begin, e.g. the search for glueball and hybrid candidates, as well as precision width measurements to pin down the nature of some of the newly discovered hadronic states. The detector is in an advanced stage of preparation and is optimized for high rate resonance and threshold scans, with modular components for specific topics such as studies of (double) hypernuclei. The completion of the full FAIR facility will provide a factor 20 higher luminosity, enabling the full precision for resolving these fundamental questions.

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